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Manipulator Control and Mechanization: A Telerobot Subsystem

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1. ABSTRACT

~~This paper describes~~ the short- and long-term autonomous robot control activities in the Robotics and Teleoperators Research Group at the Jet Propulsion Laboratory (JPL). This group is one of several involved in robotics which is an integral part of a new NASA robotics initiative called Tele obot program. ~~This paper provides~~ a description of the architecture, hardware and software, and the research direction in manipulator control. is given

Are described.

2. INTRODUCTION

The Telerobot program is a new project initiated in 1985 by NASA. The aim of this program is to develop a technology base in the areas of teleoperators, robotics, human factors, artificial intelligence, vision and other sensors, and manipulators. The objective is to develop and integrate the technologies to be used in future NASA endeavors, particularly for on-orbit assembly, maintenance, repair, and operation. To realize the goals of the program, JPL and other NASA centers have been funded to develop core technologies with broad applications in automation and robotics and to carry out a series of ground demonstrations of the developed technologies. These demonstrations are currently planned for 1988, 1990, 1993, and beyond. Each successive demonstration will evidence proof-of-concept for a higher degree of autonomy than its predecessor. The short-term objectives are set forth by the first demonstrator in 1988. This paper will give a detailed description of the hardware, software, and control strategies that have been planned to carry out the 1988 demonstration task. The long-term goals of the group's activities will also be described.

3. TELEROBOT ARCHITECTURE

A testbed is required as a general facility to test and validate theoretical developments at JPL and other NASA centers. JPL has developed a flexible and hierarchical system architecture for the Telerobot Testbed facility. Figure 3.1 illustrates the major components of this architecture. It is recognized that in the foreseeable future human intelligence will be required for complex robot task execution. The architecture is designed so that the operator can assume control or halt the autonomous task execution at any time. Certain provisions were necessary to eliminate the risk of damaging the workpieces or the manipulators by prohibiting the operator from halting the autonomous operation in some critical instances. For example, stopping the autonomous activity during a satellite capturing task could possibly damage either the arms or the satellite or both. In this particular instance the autonomous operation will acknowledge the operator's desire to stop the operation but will first execute a routine to withdraw the arms to a safe position before bringing them to a complete stop. An overview of this architecture is documented in reference [1].

On the autonomous side, the AIP (Artificial Intelligence Planner) will develop task scripts from requests made by the operator and will specify certain regions of space in which the arms must be moved based on global spatial planning. In the near-term, most of the AIP activities will be off-line. It is envisioned that the AIP will have on-line task planning and error recovery in the future.

Run Time Control (RTC) is the second subsystem in the hierarchy. This subsystem serves several important functions in the autonomous operation mode. It will receive high level task planning information from the AIP and break them down to a number of primitive operations that can be executed in the Manipulator Control and Mechanization (MCM) subsystem. This subsystem will determine collision free paths for the robot and select an appropriate one to avoid wrist and workspace singularities. RTC will keep track of the world model and update it as the manipulators modify the geometry of the environment. This subsystem will coordinate other subsystems to realize a particular task. A more detailed description of this subsystem is given in references [2] and [3].

Sensing and Perception is a subsystem which will provide acquisition and tracking capability for the tracking of known but unlabelled moving objects and position verification for fixtures on workpieces (e.g. bolts, handles, etc.). The vision system currently under development includes custom-designed image-processing hardware, and acquisition and tracking software running on a general purpose computer. More detailed information on this subsystem and its activities are documented in references [4] and [5].

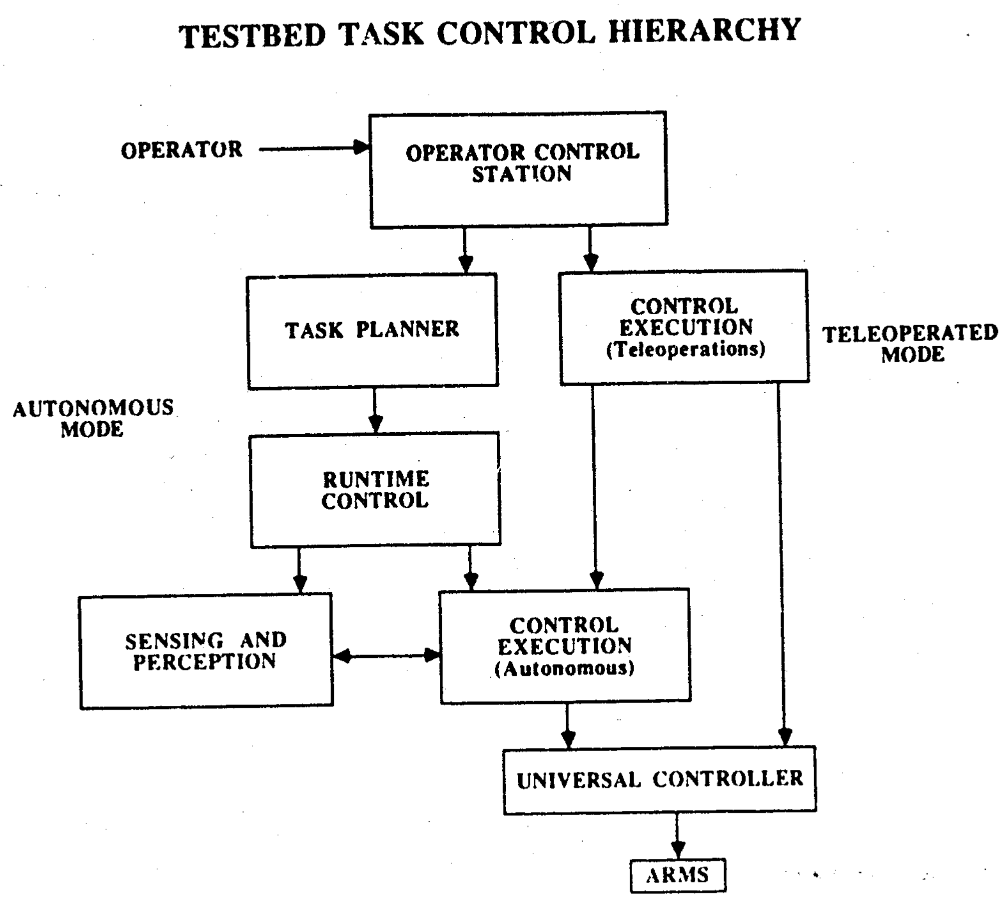

Figure 3.1 Testbed Task Control Hierarchy

Manipulator control and Mechanization (MCM) is the subsystem that is responsible for trajectory generation and low-level control of the manipulators in the autonomous mode of operation. Sections 4 and 5 will provide a detailed description of this subsystem and current research activities.

The teleoperator subsystem forms a parallel link to the autonomous hierarchy so that the operator can control the manipulators directly. The control is based on the operator generating commands by physically moving two six degree-of-freedom (DOF) force reflecting hand controllers with the remote site manipulators responding to these commands. The hand controllers themselves are six DOF manipulators with DC motors to realize force reflection, and use a distributed microprocessor computing architecture. References [7] through [9] provide a more detailed description of this subsystem.

4. MANIPULATOR CONTROL AND MECHANIZATION SUBSYSTEM

The goal of this subsystem is two-fold. It is designed to 1) provide low-level robot control for the Telerobot testbed facility and 2) furnish a research facility for testing robot control algorithms. The selection and design of the software and hardware for this subsystem were based on several factors, among which portability and extendibility were critical. Although when viewed from the Telerobot system level, MCM can be considered to be a low-level system, MCM itself has several levels of hierarchy. The software is based on a robot language, RCCL (Robot Control "C" Library), developed at Purdue University by Professors Richard Paul and Vincent Hayward [10]-[12]. A brief description of the software architecture is given later in this section.

The manipulator hardware at the present time consists of three PUMA 560 robots. One of the arms will serve as a platform for positioning and orienting a pair of stereo cameras for the Sensing and Perception subsystem. The other two arms, which will be used for single and dual arm manipulations, are mounted on lathe beds so their relative distance can be modified to accommodated various task requirements. In the future this system will be mechanized to provide servo controlled simultaneous relative positioning of the manipulators' single and dual arm operations. This will increase the work volume of the manipulators and will bring about challenging theoretical problems both in task planning and cooperating arm control. The manipulation arms are equipped with commercial (LORD Corporation) force-torque sensors with associated microprocessors. These arms are also currently equipped with simple on-off pneumatic grippers.

The testbed includes a 350 pound satellite mockup which can spin and nutate freely on a gimbal for up to several minutes, closely simulating the dynamics of a real satellite. The satellite mockup is fitted with a panel which is affixed to one of its sides by means of four screws. The removal of the panel can best be accomplished by two cooperating arms after the screws are removed. The task complexity can be increased by mounting various elements under this panel, such as PC boards and electrical connectors with cables attached. The satellite mockup is also fitted with an (EVA) fluid connector, which is a coupling device designed for transferring fluids and low pressure gases. The assembly and removal of this coupler also introduces single and dual arm force/position control problems that must be dealt with. The setup presents many realistic and complex problems for robot task planning and control. One challenging task is to track the position/orientation of the slowly spinning satellite by the Sensing and Perception subsystem, grapple with the satellite and bring it to a rest position without exerting excessive forces/torques on the arms. This task requires cooperative arm control as soon as the arms come in contact with the satellite. Figure 4.1 shows the MCM testbed facility.

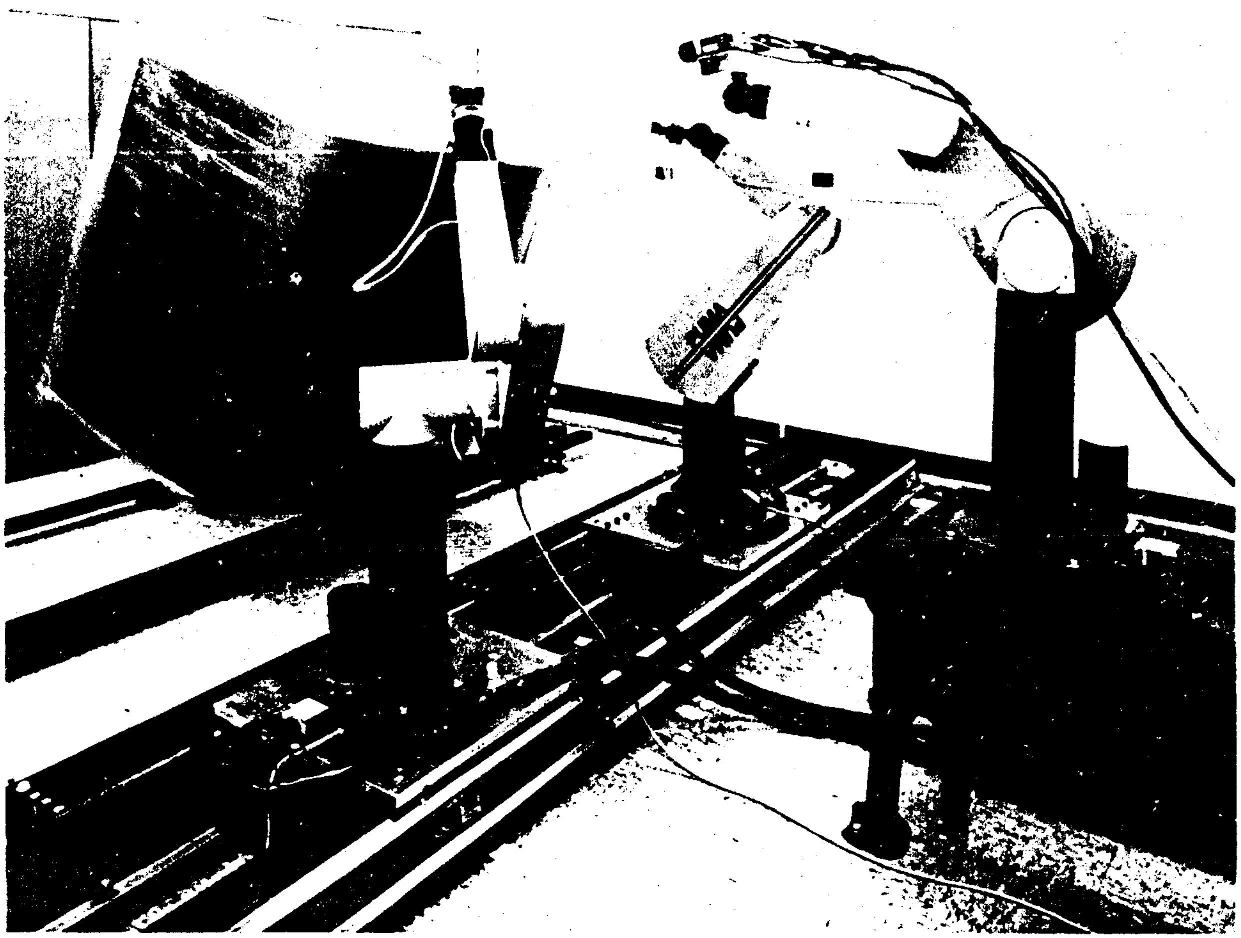

Figure 4.1 Testbed Facility at the Robotics and Teleoperators Research Group

The computing facilities at the present time are a MicroVax II, three Unimate controllers and the microprocessors of the force torque sensors. Figure 4.2 illustrates the detailed hardware schematics of MCM and its interface with RTC and Sensing and Perception. Since RCCL plays a central role in the MCM subsystem, a brief description of the language and its capatilities and limitations will be discussed below. For more detailed information see references [13] and [14].

The system software consists of a series of programs running simultaneously on various processors. Figure 4.3 shows a block diagram of the RCCL architecture. The configuration uses the Unimate controllers as low-level servo control units. The LSI 11/73 microprocessor in the Unimate controller is utilized as an I/O system to link the MicroVax II to the 6503 joint microprocessors. A hard clock constantly interrupts the I/O control program at a preselected sample rate. At every interrupt, a program which resides in the LSI 11/73 gathers information about the state of the robot arm, including joint positions and currents, front panel switch register contents, A/D converter readings, parallel port data, and teach pendant signals. The program then

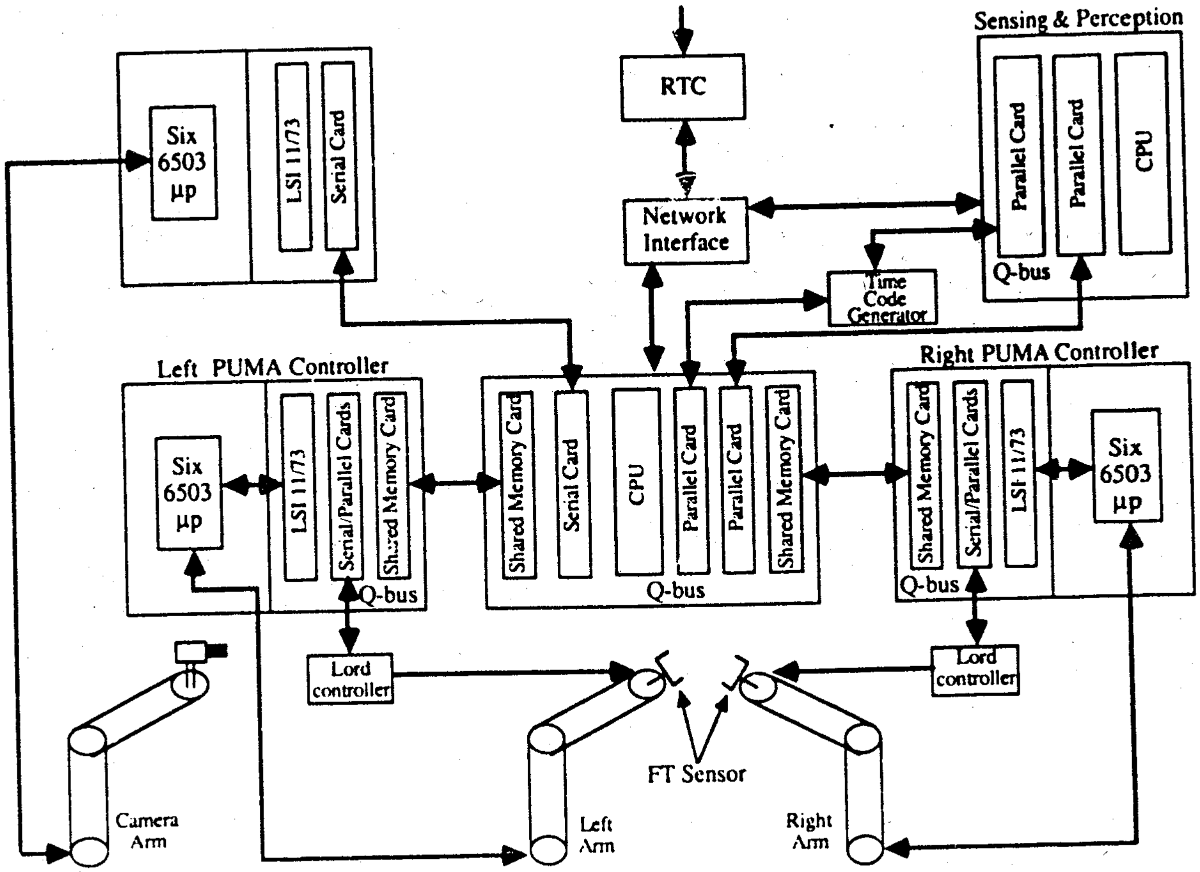

Figure 4.2 Detailed MCM Hardware and Interface

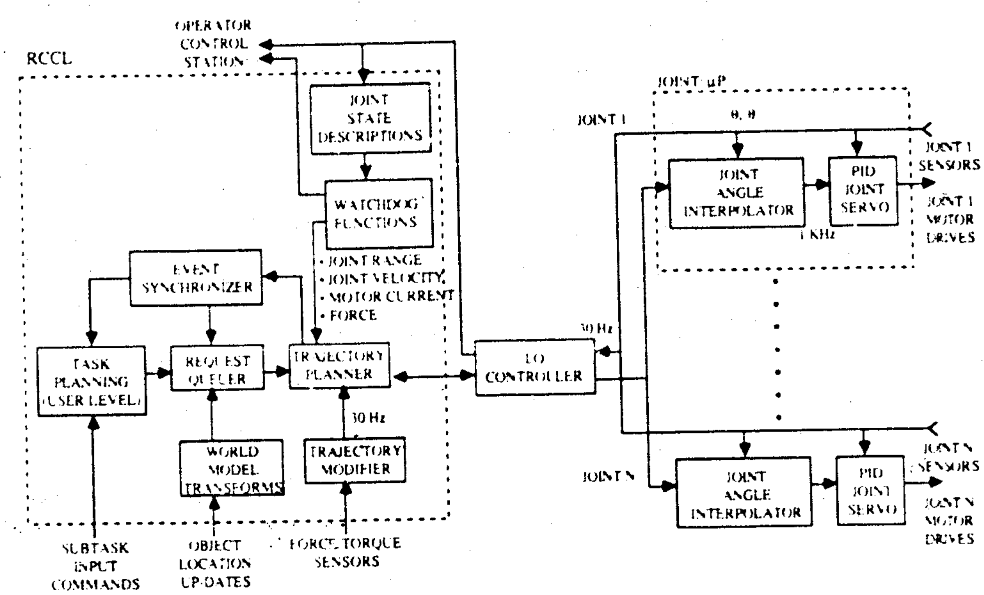

Figure 4.3 Functional Diagram of RCCL and Unimate Controller Resident Software

interrupts the control level on the MicroVax II, transmits this data, waits for the control level to return a set of joint commands, and then dispatches these commands to the required joints. The sample rate can be changed from its normal setting of 28 msec to 56, 14 and 7 msec.

The MicroVax II contains the planning and control programs, which run concurrently with each other. The planning level, which interacts with the user, operates in the normal time-sharing context and has access to all standard resources, such as files, devices, and system calls. The user, utilizing the library functions, specifies by a Cartesian frame the goal position and via points that the end-effector must pass through. The planning level forms a motion queue based on the sequence in which the user has specified the motions. High-level functions are available to change the sample rate and modify the planned path in real-time based on either an internally generated path modifier or by use of external sensors.

The control level runs in the foreground and executes a number of procedures at the sample rate of the system. When it is interrupted by the LSI 11/73 it first checks the received information for data integrity and the normal status of the arms' joint servos. The data consists of joint angle readings, motor currents, and the robot's status. In the JPL implementation, the data also includes the force/torque readings received by the LSI 11/73 once every sample time. The program then transmits the new set points that this level has computed in the last sample interval through the LSI 11/73 to the joint microprocessors. It then executes a control function (see Fig. 4.4) to calculate a new set of joint servo settings. This control function is normally a trajectory generator but, as was mentioned earlier, it can also include a user function for real-time modification of the trajectory which the user has defined at the user level. To meet the constraints imposed by the sample rate, the control level executes in the highest priority mode. The set points normally are new joint positions but can also represent motor currents for force servoing.

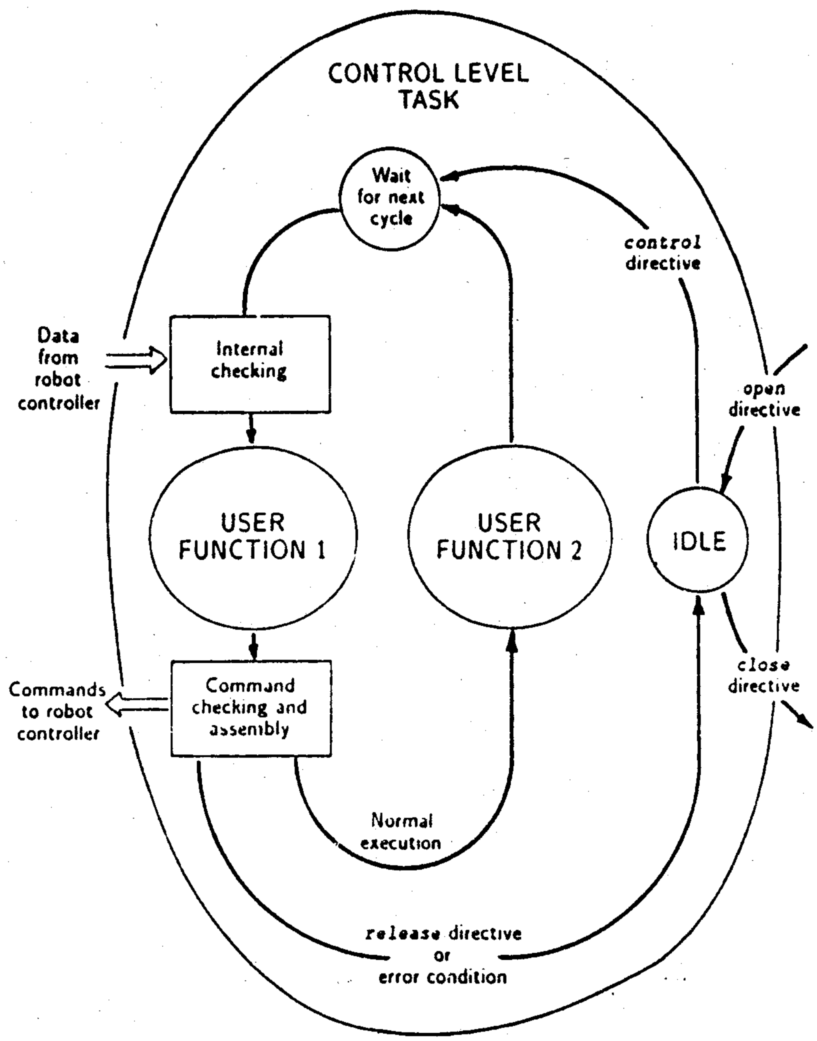

Figure 4.4 Control Level Software Block Diagram

The Telerobot subsystems will be connected to form a network with an Ethernet cable. The subsystems will communicate with each other using the 10 megabit Ethernet "physical link". Because most of the computers will be VAX's using the VMS operating system, the DECNET protocol has been selected as the basic "logical link" over the Ethernet. Since the Unix operating system does not support DECNET, an intermediate MicroVax II running under the VMS operating system is utilized as a link between the Unix MicroVax II and the other subsystems. These two microVax II's are connected to each other via a shared memory card.

Although the current setup provides a flexible and portable programming environment, there are severe problems and shortcomings that must be addressed. The current RCCL implementation at JPL is viewed as a short-term solution for the MCM subsystem. One problem with the current setup is that most sophisticated robot control algorithms require very high throughput. Presently only the kinematics of the robot is considered in generating the set points. The computation burden is on a single MicroVax II CPU which cannot meet the high throughput requirements of advanced multivariable control laws. A second problem is posed by the language, which is written for the control of a single robot arm. Any modification to the language must include the capability to plan for and control two or more arms simultaneously. A third problem lies with the Unimate controller. Although it is possible to use this controller to run arms other than Unimation's, one is limited by the speed and particular control method used in the servo controllers. In the following the we describe our plans for addressing these limitations.

Currently JPL is in the process of designing a low-level robot controller based on distributed microprocessors. Initially this controller will have the capability of controlling eight joint motors[15]. This capability can easily be extended to control more that eight joints. The first goal is to control both the PUMA 560 arms and the Universal Force Reflecting Hand Controllers. In 1989 this controller will be used to control the seven DOF space-like arms currently under development at the Oak Ridge National Laboratory under contract to the NASA Langley Research Center [16]. In addition, a distributed microprocessor-based computing facility is being developed to replace the MicroVax II computer as the MCM computer. At the present time only a preliminary design is established for this hardware. Figure 4.5 shows a preliminary block diagram of this computing facility and its integration with the joint controller system. To summarize, for 1988-1989 JPL will have three main elements for advanced manipulator control. These are 1) programmable joint controllers that can be used to control various robots, 2) an open architecture distributed microprocessor computing facility for trajectory planning and control of multiple cooperating manipulators, and 3) seven DOF modular space-like manipulators.

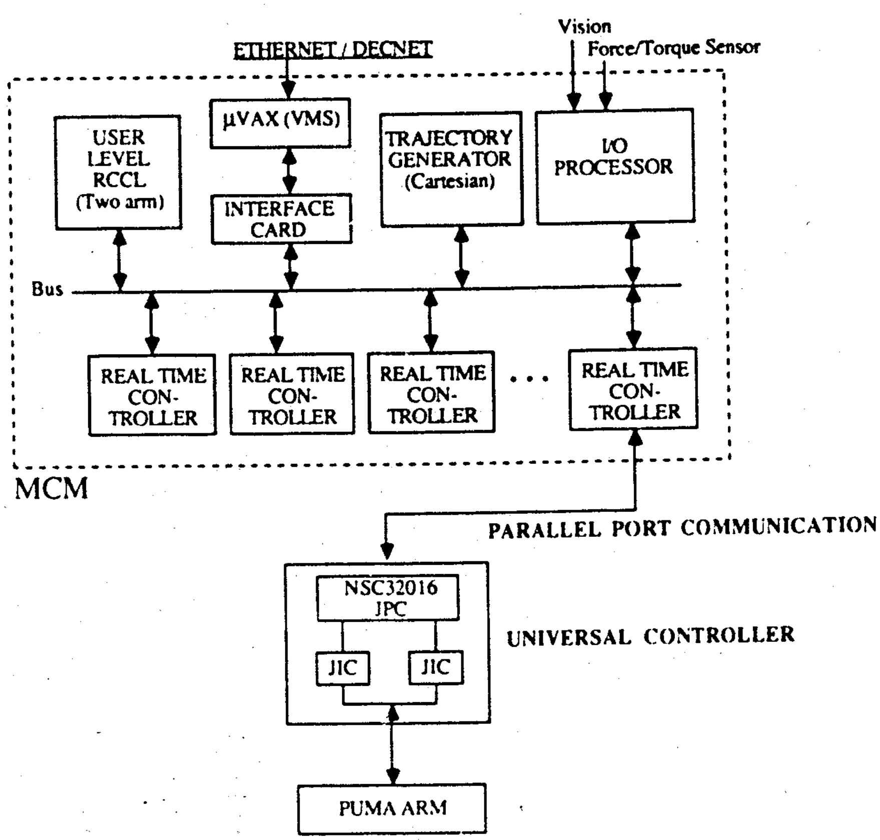

Figure 4.5 Preliminary Architecture for MCM Distributed Microprocessor Computing Facility

5. RESEARCH IN MANIPULATOR KINEMATICS, DYNAMICS AND CONTROL

Our research activity is in support of both near- and long-term goals established by the the Telerobot program. In the following we will describe the main research activities pursued by the group in manipulator control and mechanization.

5.1 Manipulator Geometry Modelling

One of the most important functions of autonomous robots is movement of their end-effectors to various locations in the work space. Tasks performed by these robots require a certain positioning accuracy. Experience with industrial robots has shown that although the relative positioning accuracy (or repeatability) is satisfactory, the absolute positioning accuracy is not acceptable. This inaccuracy is largely due to uncertainty in the manipulator's geometric parameters. Our research has resulted in a parameter identification technique to update the geometric errors of the manipulators. Both simulation and actual laboratory experiments have shown the validity of the technique.

An associated problem with the geometry calibration is the inverse kinematics problem of so called near-simple manipulators. To utilize the results obtained from the above geometric calibration one must incorporate the improved knowledge of the link parameter errors in the forward and inverse kinematics equations of the calibrated robot. Modification of the forward kinematic equations is very simple. Modification of the inverse kinematics, unfortunately, is not so easy. It is well known [17] that for a large class of robots the inverse kinematic solution can be obtained in a closed form. The condition for the existence of an analytic solution is that at least three consecutive joint axes must intersect at one point (a "simple" arm). The post-calibrated model of the robot, which more accurately represents the physical system, is that of a non-simple one. The inverse kinematic equations are solved by first finding the closed form solution for the ideal model and then computing small variations to be added to the joint angles by utilizing the Jacobian of the post-calibrated model. For more detail see references [18]-[20].

5.2 Model-based Dual Arm Control

The topic of multiple robot control is relatively new in robotics research. The extension of robot control techniques to the case of multiple manipulators is necessitated by realities encountered both for manipulating small objects and for handling large workpieces. The manipulation of objects normally requires at least two hands to simultaneously position and reorient the object so that either one or both hands can perform their respective tasks.

Our research in this area has been based on the derivation of the equations of motion in the so-called Operational Space (or Cartesian state space). We assume a general case of n cooperating robots which are holding an object rigidly. This object may also be constrained from motion in one or more dimensions by an external environment. Equations of motion are derived using the Lagrange multiplier technique. It is assumed that each manipulator is equipped with a force/torque sensor capable of measuring three orthogonal forces and torques in a given coordinate frame. The aim is to control the position of the object and its interaction forces with the environment in the sense of hybrid control of Raibert and Craig [21]. Utilizing these dynamics equations a decoupling controller in configuration space is designed to control both the position and the interaction forces of the object with the environment. Preliminary simulation studies on a simple system which consists of a pair of two-link manipulators holding a load which interacts with an environment have shown that the control technique yields excellent results. For more details please refer to references [22] and [23].

5.3 Adaptive Control of Manipulators

Adaptive control offers an appealing solution to the control problem. In adaptive robot control methods, neither the complex mathematical model of the robot dynamics nor any knowledge of the robot parameters or the payload are required to generate the control action. Adaptive control methods fall into two distinct categories, indirect and direct. In direct adaptive control methods the control action is generated directly, without prior parameter estimation. Research in this area was started by the application of adaptive control techniques to control the manipulator in joint space. Research was then extended to the control of manipulators in Cartesian space. Further research resulted in an adaptive control technique for simultaneous position and force control of manipulators. Most recently, an adaptive controller was formulated for the control of multiple cooperating robots. Simulation studies on two link manipulators have shown excellent results for all of the above adaptive controllers. Additional detail is contained in references [24]-[27].

6. CONCLUSIONS AND FUTURE RESEARCH DIRECTION

Most of the Robotics and Teleoperators Research Group's research activity in the manipulator control area is of a theoretical nature. Much effort and further research will be required to implement the proposed control algorithms. Several important realistic problems such as arm friction and backlash, joint flexibility, computational complexity resulting in low sampling rates, finite measurement resolution and measurement noise will have to be considered before a robust controller can be realized. Further theoretical work in multiple cooperative arm control and redundant arm control is currently being carried out.

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8. ACKNOWLEDGMENT

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